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Review

A review of Australian classical biological control of weeds programs and research activities over the past 12 years

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ABSTRACT

Considerable progress has been made towards the successful classical biological control of many of Australia's exotic weeds over the past decade. Some 43 new arthropod or pathogen agents were released in 19 projects. Effective biological control was achieved in several projects with the outstanding successes being the control of rubber vine, *Cryptostegia grandiflora*, and bridal creeper, *Asparagus asparagoides*. Significant developments also occurred in target prioritization, procedures for target and agent approval, funding, infrastructure and cooperation between agencies. Scientific developments included greater emphasis on climate matching, plant and agent phylogeny, molecular diagnostics, agent prioritization and agent evaluation.

1. Introduction

Australia has long been a strong proponent of classical biological control of weeds. Since the first attempts at finding agents for prickly pear, *Opuntia stricta* (Haw.) Haw., as early as 1908 and lantana, *Lantana camara* L., in 1916 there have been several outstanding successes including those of the prickly pear (for which there is a national memorial), skeleton weed *Chondrilla juncea* L. and salvinia *Salvinia molesta* D.S. Mitchell.

The aim of this review is to cover developments in classical weed biocontrol in Australia over the 12 years since the last edition of Julien and Griffiths (1998) which catalogued all agent releases made in Australia to the end of 1996. This review therefore describes progress in Australia since and including 1997 until mid 2009. The review first discusses the contribution to the general science of weed biological control under several themes and then describes those biological control programs where there were significant developments during the period.

2. Developments in Australia's biological control framework

The successful progress of biological control depends upon suitable policy, legislative, funding and infrastructure frameworks. Australia has advantages such as being a nation-continent, having achieved early biocontrol successes known to the public, having a unique native flora and enjoying political enthusiasm for biological control. Nevertheless the framework needs to evolve in response to changing times to remain effective. There have been several significant developments affecting the practice of weed biological control.

2.1. Legislation and policy

The importance of weeds was recognised on the national level with the prioritisation of Australia's worst weeds. In 1999 the 20 worst weeds were identified from a list of 71 species as the Weeds of National Significance or WONS (Thorp and Lynch, 2000). Weeds designated as WONS were targeted for funding through various national programs and this therefore influenced the resourcing of weed biological control efforts. Biological control programs against weeds not on this list required state, industry or private funding or to be an election issue. For example, fireweed, *Senecio madagascariensis* Poiret, was specifically named for biological control funding in the election manifesto of the incoming federal Labor government of 2007.

Australia has had specific procedures for gaining permission to release exotic biological control agents for many years. Recently, approval of weeds species as targets for biological control has also been formalised and is now a prerequisite for applying to release an agent. Proposals for all weed targets for biological control are

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submitted through the Australian Weed Committee, to determine whether there are any significant conflicts of interest, before they are finally approved by the Natural Resource Management Standing Committee.

Agents are still approved for release, nationally, by the Australian Quarantine Inspection Service (AQIS) under the *Quarantine Act* 1908 (Cwlth). The Minister of the Department for the Environment, Water, Heritage and the Arts (DEWHA) also has to approve new arthropod agents being added to the permitted live import list for importation under the *Environmental Protection and Biodiversity Conservation Act* 1999 (Cwlth) (EPBC Act) (Sheppard et al., 2003). The basis of the risk assessment under the EPBC Act is to adopt a "precautionary approach" to potential impacts on native biodiversity, while the parallel notion under the *Quarantine Act* of the "appropriate level of protection" (defined by the International Plant Protection Congress) applies. Under neither legislation is the potential benefit of biocontrol agents considered. Changes are underway, however, as the Department of Agriculture, Fisheries and Forestry (DAFF) is developing a new Biosecurity Act which will bring the current specific approval process for biological control agents into line with generic Import Risk Assessment (IRA) procedure. The EPBC Act is also under review.

Although Australia remains the only country to have specific biological control legislation, the *Biological Control Act* 1984 (Cwlth) and mirror state acts, to resolve conflicts of interest associated with biological control and to give legal protection to public agencies making releases, the legislation has not been invoked since 1996 when rabbit calicivirus was declared under the Act after it escaped semi-quarantine (Landstrom, 2001). The legislation has essentially become ineffective and fallen into disuse. Declaration of either targets or agents under the Act is associated with a complex enactment process and high costs (a required public enquiry) leading to inaction and reluctance over who will pay (McLaren et al., 2006). For weeds, only Paterson's curse, *Echium plantagineum* L., and four of its agents (at the inception of the Act) and blackberry rust, *Phragmidium violaceum* (Schultz) Winter, (the right to redistribute illegally introduced strains of the blackberry rust) have ever been declared under the Act. Due to its disuse the Act also remains unchallenged legally concerning the protection it offers agencies undertaking releases. While attempts have been made to review the Act, each time the review outcome is essentially that new legislation would be the only way to provide a more effective legal process for biological control.

2.2. The Cooperative Research Centres

In 1991, the Australian Government initiated the Cooperative Research Centre (CRC) Program of centres of excellence. Australian weed biological control was associated with three of these; the CRC for Tropical Pest Management (1991–1998) and more importantly the CRC for Weed Management Systems (1995–2001) that evolved into the CRC for Australian Weed Management (2001–2008). These CRCs played a pivotal role in bringing together the weed biological control research community around research and extension across state agencies, the CSIRO[1] and the universities and made significant contributions to the underlying science of biological control. Specific collaborative projects and workshops addressed key biological control issues such as host-specificity testing (Withers et al., 1999), selection, testing and evaluation of agents (Roush, 2003), the ecological basis for agent selection (Raghu and van Klinken, 2006) establishment of agents (Anon, 2008b; Spafford et al., 2008) and evaluation of impacts (Anon, 2008a). Funding also went into initiating new programs and engaging Ph.D. students to increase the science following agent release and conducting the evaluation of old programs.

One of the most significant studies for weed biological control from the CRC for Australian Weed Management was a contracted independent economic evaluation of the costs and benefits of Australia weed biological control programs (Page and Lacey, 2006). This study analysed all Australian projects where some economic data were available (notable exceptions were St John's wort, *Hypericum perforatum* L. and the docks, *Rumex* spp. programs) and concluded that Australia's overall effort had resulted in an overall benefit cost ratio of 23:1. The outstanding successes from an economic point of view included *Ambrosia artemisiifolia* L., *Chondrilla juncea* L., *Cryptostegia grandiflora*, *Echium plantagineum*, and *Opuntia* spp.

2.3. Overseas field stations and exploration

Exploration within native ranges is a critical initial component of classical biological control of weeds (Goolsby et al., 2006b; Sheppard et al., 2006). This has been achieved either through sending scientists overseas in collaboration with local scientists and research agencies, through establishment and maintenance of Australian overseas facilities or through using the overseas laboratories of other agencies (e.g. USDA or CABI). CSIRO continues to maintain two overseas facilities, at Montpellier in France (Sheppard et al., 2008) (used regularly by Victorian Department of Primary Industries (VicDPI)) and at Veracruz in Mexico, from which 16 agents have been released in Australia against four weed targets. A recent study of the economic returns on investment of Australia's funding its own overseas laboratory in France for 40 years estimated a conservative return on investment of 27:1 in additional to high science impact for the discipline (Sheppard et al., 2008).

The CSIRO and VicDPI support native range research in Argentina in collaboration with Argentinean Universities and the USDA South American Biological Control Laboratory. This work has recently focussed on agents for *Nassella* spp., *Cabomba* spp., *Phyla canescens* (Kunth) Greene, *Alternanthera philoxeroides* (Mart.) Griesbach, *Parkinsonia aculeata* L. and *Heliotropium amplexicaule* Vahl. Queensland Primary Industries & Fisheries (QPIF) supported a field station from 1999 to 2003 in Pretoria, South Africa to work on *Acacia nilotica* (L.) Delile, *Bryophyllum* spp. and *Sporobolus* spp., while VicDPI posted staff to the South African Agricultural Research Council-Plant Protection Institute and CSIRO contracted staff from the same institute for work on *Asparagus asparagoides* (L.) Druce, *Senecio madagascariensis* Poir., and *Chrysanthemoides* spp. during the last 10 years. Similarly South Africa undertook short term exploration in Australia for agents for various projects, often assisted by Australian colleagues.

In Brisbane, the CSIRO hosts, staffs and now runs the USDA-ARS Australian Biological Control Laboratory which searches for potential agents for American pests of Australian or South-East Asian origin (Balciunas and Burrows, 1993; Galway and Purcell, 2005; Goolsby et al., 2001, 2002, 2003; Purcell et al., 2007; Purcell and Goolsby, 2005) particularly *Lygodium* ferns, the shipment of *Cytobagous salviniae* Calder and Sands to control *Salvinia molesta* Mitchell, and the very successful program against the paperbark tree *Melaleuca quinquenervia* (Cav.) S.T. Blake in Florida (Tipping et al., 2009).

[1] *Abbreviations used:* CSIRO, CSIRO Entomology; NSWDEC, New South Wales Department of Environment and Conservation; NSWDPI, New South Wales Department of Primary Industries and its predecessor the NSW Department of Agriculture; NTDNR, Northern Territory Department of Natural Resources; QPIF, Queensland Primary Industries & Fisheries (This designation includes work undertaken by the Department of Natural Resources and the Department of Lands under earlier arrangement of the departments); SARDI, South Australian Research and Development Institute; TIAR, Tasmanian Institute of Agricultural Research; VicDPI, Victorian Department of Primary Industries, and other Victorian Government entities that have formerly administered weed biological control research and development.

International cooperation continues to be a feature of Australian weed biological control. Agents found by South African scientists in the native ranges were then brought into Australia for lantana, cat's claw creeper, *Macfadyena unguis-cati* (L.) Gentry, and Madeira vine, *Anredera cordifolia* (Tenore) Steenis. Program costs and economies of scale have led to Australian joint projects with New Zealand on *Chrysanthemoides monilifera* (L.) Norlindh, *Alternanthera philoxeroides* (Martius) Grisebach, *Cytisus scoparius* L. and *Ulex europaeus* L. and with the USA on *Genista monspessulana* (L.) L. Johnson. Projects on weeds in Australia continue to benefit other countries, particularly developing countries, with related weed problems. Following its success in Australia, the leaf beetle *Calligrapha pantherina* Stål was sent to Papua New Guinea in 1999 and soon provided effective control of *Sida* spp. (Kuniata and Korowi, 2004).

2.4. Facility infrastructure

The need to test increasing numbers of native plants during host-specificity testing since the promulgation of the *Wildlife Protection Act* (1982) (C with) and also the costs of maintaining staff and facilities overseas has led to increasing use of quarantine facilities within Australia to undertake this risk assessment. Approved quarantine facilities are required to allow research on plant pathogens as well as invertebrate biocontrol agents. Australia currently has five facilities approved for housing exotic invertebrate weed biocontrol agents (QPIF at Sherwood, CSIRO at Long Pocket, CSIRO at Black Mountain, VicDPI at Frankston and the Waite facility comanaged by SARDI and The University of Adelaide) and one facility that has been approved for work on certain plant pathogens (CSIRO at Black Mountain). Another facility was completed in Perth but has not yet been approved due to numerous problems with security and construction quality. Two new facilities are presently being planned for weed biological control work. The construction of these facilities is fortunately coinciding with changes of standards for quarantine facilities which are presently being undertaken by AQIS following reviews of general quarantine procedures (Beale et al., 2008; Nairn et al., 1996) and several apparent escapes from Australian quarantine facilities in the late 1990s.

A 400 m^2 quarantine facility (with 200 m^2 of glasshouses) is being built on the roof of the new Ecosciences Precinct in Brisbane. This quarantine facility and supporting glasshouses, shade houses and non-quarantine laboratory facilities will be shared by QPIF and CSIRO. The quarantine facility will be built to QC3 standard and will include six quarantine glasshouses suitable for both arthropods and pathogens. A feature of the glass house design will be a possibly unique double glazing with glass panels separated by a 30 cm air space. Liquid wastes from the quarantine will be sterilized by the highly energy efficient heat transfer system of Actini (registered trademark).

Under a Victorian Department of Primary Industries/Latrobe University Joint Venture a Biosecurity complex is being constructed at Latrobe University's Bundoora campus in Melbourne. The facility will replace VicDPI's laboratories and glasshouses at a number of sites including the biological control facilities at Frankston. Of the containment areas being constructed, the biological control facilities will comprise 270 m^2 of QC3 (including 100 sq m of glasshouses) and 250 m^2 of QC2 (including 80 sq m of glasshouses). Extensive areas of non-containment plant and insect growth rooms, glasshouses and polyhouses will also be constructed at both these facilities, ensuring adequate facilities for mass rearing agents.

Weed biological control quarantine facilities are distinguished from other quarantine facilities by usually incorporating glasshouses within the quarantine envelope. They are also usually supported by non-quarantine glasshouses used to grow test plants and the target weeds. Modern building codes have caused problems with selection of glasshouse glazing in that non-laminated glass can no longer be used for safety reasons. Laminated glass and the alternative polycarbonates do not allow transmission of UV light which is an important spectrum influencing insect–plant interactions (Rousseaux et al., 2004).

By 2012 it is anticipated that Australia will have five quarantine facilities available for weed biological control research; the two new facilities described above, CSIRO facilities at Black Mountain, Canberra and Floreat Park, Perth, and the facility at the Waite Institute.

3. Scientific developments

The progression of the various biological control projects gives the opportunity to improve the science behind biological control and particularly to improve the safety, efficiency and efficacy of projects. Further, classical biological control is an opportunity to explore more general issues relating to insect/plant interaction, establishment of invasive species and climate and biotype matching. This section expands on some recent developments in classical weed biological control in Australia following on from a review by Briese (2004).

3.1. Plant biogeography

Studies on the biogeography of the target weed using molecular markers have revealed insights useful for biological control. Here we present several examples.

Acacia nilotica is a widespread species with nine subspecies found between the Indian subcontinent and southern Africa and for this weed it was important to know the origin of Australian weedy population. Although morphologic (Brenan, 1983) and leaf phenolic studies (Hannan-Jones, 1999) suggested that the Australian populations were from India, the question was resolved by molecular genetic distance studies using patterns of DNA sequence variation (Wardill et al., 2005, 2004b). They confirmed that the Australian *Acacia nilotica* populations are mostly comprised of subspecies *indica*, but in addition, some individuals were found to be genetically identical to an unidentified Pakistan genotype not previously reported from Australia (Wardill et al., 2005).

The discovery that the current broad distribution and deep genetic structuring of *Parkinsonia aculeata* reflects very old dispersal events (Hawkins et al., 2007) was significant for agent exploration. The Venezuelan, Central American and Argentinean samples differed strongly from the North American ones. This genetic information, in combination with observations made during field trips in South America, indicates that *Parkinsonia aculeata* is native to South America and arrived there millions of years ago (Hawkins et al., 2007). These populations may harbour unique and specific co-evolved natural enemies and new surveys are being conducted in Central and South America to complement the original surveys in North America (Woods, 1992). Additionally the Venezuelan samples most closely matched the Australian ones indicating that surveys there may be particularly fruitful.

Genetic studies have also been used to investigate the origin of exotic (including Australian) populations of cat's claw creeper, *Macfadyena unguis-cati*, by using polymorphic chloroplast microsatellites to estimate haplotypic diversity across the native range and then to match the genetic signature of the exotic populations to these (D. Sigg et al., unpublished). It was found that over 90% of samples from countries where the weed had been introduced belonged to a single haplotype that represented samples from Paraguay and other areas in the southern native range.

Chloroplast microsatellites were also used to determine the patterns of phylogenetic structure in native and exotic populations of *Jatropha gossypiifolia* L. and to establish the origins of the exotic populations. Australian populations were found to result from multiple introductions from diverse source locations and no reduction in genetic diversity was evident (Prentis et al., 2008). The significance of this finding is that the search for agents needs to include the whole range of the weed without regard for subspecies or biotypes.

Both genetic analysis and complete karyotype analysis are also being used to identify the origin of *Alternanthera philoxeroides* in Australia, New Zealand and China (S. Schooler, CSIRO Entomology, personal communication). This information will help select areas for native range exploration.

3.2. Agent selection

Australia has invested significant resources in trying to improve the science behind agent selection. Progress was reviewed by Briese (2004) and a special issue on the subject (Raghu and van Klinken, 2006) expanded our understanding further (Sheppard, 2006). Several papers argue that agent selection is highly dependent on the type of weed, its reproductive system, on the ecological, abiotic and management context in which that weed occurs, and on the acceptable goals and impact thresholds required of a biological control program. These papers defined a framework for likely effective agents in different contexts (Adair et al., 2006; Dhileepan et al., 2006b; Schwab and Raghu, 2006; van Klinken, 2006; van Klinken and Raghu, 2006) and for plant pathogens (Morin et al., 2006c). Raghu et al. (2006) define a process for agent selection in the exotic range based on weed demography and plant response to herbivory, while Schooler et al. (2006) and Wirf (2006) describe exotic range experimental approaches to define the desirable qualities of effective agents. The importance of native range studies in determining agent effectiveness for tropical (Goolsby et al., 2006b) and temperate systems (Sheppard et al., 2006) was illustrated. Several studies reviewed the agent prioritisation approach in ongoing biological control programs (Briese, 2006; Morin and Edwards, 2006).

3.3. Taxonomic barcoding

Accurate identification of organisms discovered during survey has always been an issue for classical biological control. The problem is becoming more serious with the depletion, world wide, of taxonomic expertise and the understandable increased reluctance of regulatory bodies to allow unknown or partially identified organisms into the country. One possible alternative to conventional identification of organisms is identification by DNA barcodes (Mitchell, 2008). Further applications of this technique might be the identification of damaging immature stages, the early elimination of known pest species, or quality control checks for laboratory colonies that might be contaminated by a second species (Mitchell, 2008). Barcoding also provides a powerful means of revealing the existence of cryptic species or variation in host range within haplotypes of a species (Goolsby et al., 2006a).

3.4. Climate assessment

Climate matching software has replaced climadiagrams (Walter and Lieth, 1967) as the standard tool to assist the searching and selection of weed biological control agents (Briese, 2004). The various software packages available have advantages and disadvantages (Kriticos and Randall, 2001). Though CLIMEX® (Sutherst et al., 2004) has become the dominant software, other software packages such as CLIMATE (Pheloung, 1996) are also being used (Kwong et al., 2008).

Climate matching can be useful at various phases of a biological control project (Senaratne et al., 2008) including the selection of areas within the native range for surveying (Dhileepan et al., 2006b; Rafter et al., 2008b; Senaratne et al., 2006), prioritisation of potential agents found by survey based on predicted efficacy (Zalucki and van Klinken, 2006), selection of plant species for host-specificity testing, justification for releasing possibly oligophagous agents (Palmer et al., 2007) and the selection of areas in which to release approved agents (Heard et al., 2009; Palmer et al., 2007). A further use of climate matching applications will be to predict the effects of climate change on both target weed and agent.

3.5. Host-specificity testing

Significant improvements have been made to host-testing techniques, particularly in relation to efficiency and also reduced public tolerance for non-target attack on native flora. The centrifugal phylogenetic method (Wapshere, 1974) remains the underlying basis for selection of plant species for testing. However recent advances in molecular phylogenies found on the Angiosperm Phylogeny Website (Stevens, 2001 onwards) and other science advances have led to significant refinements to this system being proposed, academically accepted (Briese, 2005; Roush, 2003) and implemented (Briese and Walker, 2008). However, Briese (2004) recognised that for full acceptance, engagement is necessary with the decision making regulatory authorities, who have traditionally wanted to retain the concept of safeguard species for public acceptance. In Australia at least, regulators appear to be moving away from a specific process for the release of classical biological control agents towards a more generic process for all importations founded around the process of Import Risk Assessment (see above). Scientific advances in the analysis of direct risks of weed biological control agents to non-target plants both in Australia and overseas have been recently reviewed (Sheppard et al., 2005).

3.6. Laboratory cultures

A long held concern of biological control practitioners is that insect populations may lose genetic diversity while they are held in culture, particularly while in quarantine (Hopper et al., 1993; Roush, 2003).

This problem was investigated using the geometrid, *Chiasmia assimilis* (Warren), which had been released for prickly acacia, to determine the best practices for the collection, breeding and genetic management of insects being reared for release and establishment as biological control agents (Wardill, 2006; Wardill et al., 2004a). Using five microsatellite markers (Wardill et al., 2004c) they measured changes in allele frequencies between group reared lines of insects (the usual breeding practice) and isofemale line rearing methods and provided evidence that there are deleterious effects from inbreeding on this insect.

Laboratory adaptation, inbreeding depression and/or population bottlenecks of populations of the horehound plume moth *Wheeleria spilodactylus* (Curtis) were also found to be the cause of the failure of this species to establish in South Australia. Newly imported populations of the plume moth readily established in the field on the target weed horehound *Marrubium vulgare* L. (Clarke, 2001).

3.7. Integrating biological control with other weed management approaches

The critical issue of integrating biological control within the broader, integrated management of weeds has been recognised (Briese, 2004). One case study is presented here. To investigate whether biological control of *Mimosa pigra* L. could be integrated with other options, a large-scale experiment was performed to measure the impact of herbicides, fire, and bulldozing, either alone or in combination, on both *Mimosa pigra* and five biological control agents that were abundant at the site (Paynter and Flanagan, 2004). In isolation, herbicide, bulldozing, and fire were not effective, but several combinations of techniques cleared *Mimosa pigra* thickets and promoted establishment of competing vegetation that inhibited *Mimosa pigra* regeneration from seed. Some effective treatment combinations were predicted by Buckley et al. (2004) to succeed only in combination with biological control. Depending on the species, biological control agent abundance on surviving *Mimosa pigra* plants was either unchanged or increased following herbicide and/or bulldozing treatments. All agents recolonised regenerating *Mimosa pigra* within one year of the fire treatment and *Neurostrota gunniella* (Busck) populations increased dramatically. By reducing *Mimosa pigra* populations from monocultures to smaller patches or individual plants, control treatments increased the ratio of "edge" plants to "thicket" plants and therefore the proportion of plants susceptible to *Neurostrota gunniella* attack. In contrast to *Neurostrota gunniella*, *Carmenta mimosa* Eichlin and Passoa declined dramatically following the fire. Paynter and Flanagan (2004) concluded that integrating control techniques can successfully control dense *Mimosa pigra* thickets and biological control integrates well with other control options and should lead to significant cost reductions for *Mimosa pigra* management.

3.8. Non-target impacts

There has been increased interest, worldwide, in non-target impacts caused by biological control agents. In Australia any possible non-target impacts on native flora would create difficulties getting permission to release under the EPBC 1999. Three instances of non-target attack have occurred in Australia since 1996 and there has been one instance when an insect was rejected because of perceived attack on a native plant.

The membracid *Aconophora compressa* Walker was released in Australia in 1995 for lantana. However it also attacked fiddlewood, *Citharexylum spinosum* L. (on which it increased to huge numbers causing defoliation of large trees and other problems associated with its honeydew production) and to a lesser extent other mainly verbenaceous garden plants (Palmer et al., 2004). From the host-testing perspective, fiddlewood had not been included in the host test list probably because it was not recognised as verbenaceous and because it was no longer a popular ornamental. The initial attack on fiddlewood and subsequent 'overflow' onto other ornamentals caused considerable angst with affected homeowners in Brisbane but surprisingly little concern from the scientific community although it generated several studies to investigate various aspects (Dhileepan and Snow, 2006; Dhileepan et al., 2005b,c; Griffiths and King, 2005; Manners et al., 2006; Snow and Dhileepan, 2008).

The gracillariid moth, *Neurostrota gunniella*, was released in Australia in 1989 against *Mimosa pigra* although it was recognised that it might occasionally use *Neptunia* spp. as hosts. *Neurostrota gunniella* established widely and became abundant on the target weed, which grows sympatrically with at least one *Neptunia* species. Later investigations indicated that most *Neptunia major* plants adjacent to *Mimosa pigra* thickets were attacked at relatively low intensity and that *Neptunia major* growing in the absence of *Mimosa pigra* was not attacked (Taylor et al., 2007). Similarly, the pyralid moth *Euclasta whalleyi* Popescu-Gorj and Constantinescu was introduced into Australia in 1988 for the biological control of rubber vine, *Cryptostegia grandiflora* (Roxb.) R. Br., despite test results predicting it might also attack the related native vine *Gymnanthera oblonga* (Burm. F.) P.S. Green. Ten years after release, the moth became widespread and damaging on rubber vine, but minor attack occurred on *Gymnanthera oblonga* only when it is growing in close association with rubber vine plants (McFadyen et al., 2002).

On the other hand, one prospective agent received a conservative assessment and was refused permission to release. The chrysomelid beetle *Charidotis auroguttata* (Boheman) was studied for biological control of cat's claw creeper, and found to have a very narrow host range (Dhileepan et al., 2005a). Although the insect could complete a life-cycle on *Myoporum boninense australe* Chinnock, it was very evident that survival was so poor that the insect could not survive on that plant under natural conditions.

Willis et al. (2003) identified 17 agents of the 164 released in Australia to have the potential to utilise 30 non-target native species. Four of the agents were identified by Willis et al. (2003) as requiring urgent attention, due mainly to close associations of the targets and closely related native species, and laboratory evidence that these natives were capable of supporting complete development. That review prompted studies on several of these species including the work on *Euclasta whalleyi* and *Neurostrota gunniella* described above.

4. Contemporary weed biological control programs

With several groups working on weed biological control, considerable progress has been made to the programs listed below.

4.1. Acacia nilotica subsp. indica (Benth.) Brenan

Prickly acacia, *Acacia nilotica* subsp. *indica*, remains one of the worst woody weeds of northern Australia (Mackey, 1997) and is a WONS (Thorp and Lynch, 2000). Pakistan (Mohyuddin, 1981) and Kenya (Marohasy, 1995) were surveyed for agents resulting in three agents being released in Australia (Lockett and Palmer, 2003). Further survey on *Acacia nilotica* subsp. *kraussiana* (Benth.) Brenan was undertaken in southern Africa from 1997 to 2002 (Stals, 1997). Three new agents (Table 1) were released after 1997 while others were investigated but not released (Palmer and McLennan, 2006; Palmer and Witt, 2006; Witt et al., 2005, 2006). One of the new agents, *Chiasmia assimilis*, has established and causes widespread defoliation in coastal areas.

A new phase has recently been implemented involving surveys in India by staff of Indian institutions (Dhileepan, 2009). This phase involves surveys in areas in India climatically similar to western Queensland (Dhileepan et al., 2006b; Senaratne et al., 2006).

4.2. Alternanthera philoxeroides (Martius) Grisebach

Native to South America, this amphibious plant, commonly known as alligator weed, is a serious invader in North America, Asia and Australia. In USA, China, New Zealand and Australia, the introduced biocontrol agent *Agasicles hygrophila* Selman and Vogt has successfully controlled aquatic populations in warmer areas but not terrestrial populations or those in cooler areas (Julien and Griffiths, 1998). In 2003, surveys commenced for agents effective in terrestrial and cooler areas and several potential new candidates were identified. The first three agents imported into quarantine (*Amynothrips andersonii* O'Neill, *Disonycha argentinensis* Jacoby, and *Clinodiplosis althernantherae* Gagne) failed host-specificity tests by completing their life-cycle on Australian native *Alternanthera* spp. Attention has shifted to other insects (in particular, *Systena nitentula* Bechyné which is currently being tested in quarantine) and pathogens while the search for safe and effective agents continues (Schooler and Julien, 2008).

4.3. Anredera cordifolia (Tenore) Steenis

Madeira vine, *A. cordifolia*, is a serious environmental weed in south-eastern Queensland and New South Wales (Vivian-Smith

Table 1
Exotic species released for the first time as weed biological control agents in Australia since 1996.

Weed	Agent	Date of release and research organisation	Outcome
Acacia nilotica subsp. *indica* (Benth.) BrenanPrickly acacia(Mimosaceae) Ex Indian subcontinent	*Chiasmia assimilis* (Warren) (Lepidoptera: Geometridae) Ex Kenya and South Africa	1999 QPIF	About 150,000 released at 32 sites in Queensland. Outbreak populations defoliating trees have been observed at coastal sites since 2004 (Palmer et al., 2007).
	Chiasmia inconspicua (Warren) (Lepidoptera: Geometridae) Ex Kenya	1998 QPIF	About 72,000 released at 62 sites mostly in western Queensland. No establishment (Palmer et al., 2007).
	Cometaster pyrula (Hopffer) (Lepidoptera: Noctuidae) Ex South Africa	2004 QPIF	About 45,000 released, mostly in coastal Queensland. Establishment not confirmed (Anon, 2008c; Palmer and Senaratne, 2007).
Asparagus asparagoides L. DruceBridal creeper(Asparagaceae) Ex southern Africa	*Crioceris* sp. (Coleoptera: Chrysomelidae) Ex South Africa	2002 CSIRO	Released at 46 sites across southern Australia with an average release size of 400. Established at a few sites (Morin et al., 2006d).
	Puccinia myrsiphylli (Thuem) Wint. (Basidiomycota: Uredinales) Ex South Africa	2000 CSIRO	Released at over 1700 sites (Morin et al., 2006d). Established readily across southern Australia, causing major epidemics that significantly and rapidly reduced the weed's density, particularly in moist coastal areas (Morin and Edwards, 2006).
	Zygina sp. (Hemiptera: Cicadellidae) Ex South Africa	1999 CSIRO	Released at over 850 sites across southern Australia. Established across the country causing defoliation (Morin and Edwards, 2006; Morin et al., 2006d).
Baccharis halimifolia L. Groundsel bush(Asteraceae) Ex USA	Puccinia evadens Hark (Uredinales: Puccinaceae) Ex Florida	1997 QPIF	Fifty inoculations made at 39 coastal sites in southern Queensland. Well established over the weed's range and severe dieback has been observed (Tomley and Willsher, 2002).
Chrysanthemoides monilifera subsp. *monilifera* (DC.) T. Norl.(boneseed) Ex South Africa	*Aceria* sp. (Acari: Eriophyidae) Ex South Africa	2008 CSIRO, VicDPI	Too early to assess if it has established.
	Mesoclanis magnipalpis Bezzi (Diptera: Tephritidae) Ex South Africa	1998 CSIRO, VicDPI	Eleven releases were made in Victoria and South Australia but no establishment (Downey et al., 2007; Morley and Morin, 2008).
	Tortrix sp. (Lepidoptera: Torticidae) Ex South Africa	2000 CSIRO, VicDPI, TIAR, NSWDEC, NSWDPI	Released at 67 sites in Victoria, South Australia and Tasmania. No establishment (Downey et al., 2007).
Chrysanthemoides monilifera subsp. *rotundata* (DC.) T.Norl.(bitou bush) Ex South Africa	*Mesoclanis magnipalpis* (Diptera: Tephritidae) Ex South Africa	2005 VicDPI	Released at six sites but failed to establish.
	Tortrix sp. (Lepidoptera: Torticidae) Ex South Africa	2001 CSIRO, VicDPI, TIAR, NSWDEC, NSWDPI	Released at 45 sites in NSW. Established at some sites (Downey et al., 2007) but not contributing to control.
Cytisus scoparius (L.) LinkScotch broom (Fabaceae) Ex central and southern Europe	Aceria genistae (Nalepa)(Acari: Eriophyidae) Ex Europe	2008 VicDPI, CSIRO, NSWDPI	Released in Victoria. Establishment not yet confirmed.
	Arytainilla spartiophila F.(Hemiptera: Psyllidae) Ex Europe	2002 CSIRO, SARDI	Locally established. Re-assessment required.
Emex australis Steinh. spiny emex(Polygonaceae) Southern Africa	Apion miniatum (Germar) (Coleoptera: Apionidae) Ex Israel	1998 CSIRO	Failed to establish (Scott and Yeoh, 2005).
Heliotropium amplexicaule Vahl Blue heliotrope(Boraginaceae) South America	Deuterocampta quadrijuga Stål (Coleoptera: Chrysomelidae) Ex Argentina	2001 CSIRO	Established and now causing significant damage in some areas.
Jatropha gossypiifolia L. Bellyache bush(Euphorbiaceae) Ex South America	*Agonosoma trilineatum* (F.) (Hemiptera: Scutelleridae) Ex Venezuela	2003 CSIRO, QPIF, NTDNR	Over 38,000 were released at various sites in northern Queensland and the Northern Territory (Dhileepan, 2009). No establishment.
Lantana camara L. Lantana(Verbenaceae) Ex Central and South America	*Falconia intermedia* (Distant) (Hemiptera: Miridae) Ex Mexico via South Africa	2000 QPIF	Large numbers released at 51 sites in Queensland and northern NSW (Day et al., 2003a). Local establishment and severe chlorosis has occurred (Anon, 2008c; Taylor et al., 2008).
	Ophiomyia camarae Spencer(Diptera: Agromyzidae) Ex Florida via South Africa	2007 QPIF	Released at 35 sites with leaf mines being observed at 12 sites (M. Day unpublished data).
	Prospodium tuberculatum (Spegazzini) Arthur(Uredinales: Puccinaceae)Ex Brazil via UK	2001 QPIF	Over 500 releases made in Queensland and northern NSW (Day et al., 2003a). Widely established and leaf drop is occurring (Anon, 2008c; Taylor et al., 2008).

Table 1 (*continued*)

Weed	Agent	Date of release and research organisation	Outcome
Macfadyena unguis-cati (L.) GentryCat's claw creeper(Bignoniaceae) Ex Central and South America	*Carvalhotingis visenda* (Drake and Hambleton)(Hemiptera: Tingidae) Ex Brazil and Argentina via South Africa	2007 QPIF	Many releases made in Queensland and NSW. Local establishment and damage has occurred (Anon, 2008c; Dhileepan et al., 2007b).
	Hypocosmia pyrochroma Jones (Lepidoptera: Pyralidae) Ex Brazil and Argentina via South Africa	2007 QPIF	Presently being released in coastal Queensland and northern NSW. Too early to assess establishment (Anon, 2008c; Dhileepan et al., 2007a,b).
Marrubium vulgare L. White horehound Lamiaceae Ex Europe, Asia, North Africa	*Chamaesphecia mysiniformis* Rambur (Lepidoptera: Sessidae) Ex Spain	1997 VicDPI, NSWDPI	Released and established in Victoria (Sagliocco and Weiss, 2004), NSW and South Australia.
Mimosa pigra L. Mimosa, Giant sensitive bush(Mimosaceae) Ex Central and South America	*Leuciris fimbriaria* Stoll (Lepidoptera: Geometridae) Ex Mexico	2004 CSIRO, NTDNR	Over 23,000 released by 2006 in Adelaide, Mary and Finniss River catchments (Routley and Wirf, 2006) and establishment recently confirmed (N. Burrows, NTDNR, personal communication).
	Macaria pallidata Warren (Lepidoptera: Geometridae) Ex Mexico	2002 CSIRO, NTDNR	Over 37,000 released in the Adelaide, Finniss and Daly River catchments. It has established and spread widely (Routley and Wirf, 2006).
	Malacorhinus irregularis Jacoby (Coleoptera: Chrysomelidae) Ex Mexico	2000 CSIRO, NTDNR	Over 34,000 released in the Northern Territory where it established. Numbers and distribution varied with soil moisture conditions (Heard et al., 2005; Routley and Wirf, 2006).
	Nesaecrepida infuscata Schaeffer (Coleoptera: Chrysomelidae) Ex Mexico	2007 CSIRO, NTDNR	Several hundred adults and thousands of eggs released from 2007. Too early to assess establishment.
	Sibinia fastigiata Clark (Coleoptera, Curculionidae)	1997 CSIRO, NTDNR	Over 2000 field collected adults released in Australia. No evidence of establishment (Heard and Paynter, 2009).
Onopordum spp. Scotch and Illyrian thistles(Asteraceae)Europe	*Botanophila spinosa* Rondani (Diptera: Anthomyiidae) Ex France	2000 CSIRO	No sign of establishment (Roush, 2003).
	Eublemma amoena Hübner (Lepidoptera: Noctuiidae) Ex France	1998 CSIRO	Locally established but are susceptible to drought.
	Trichosirocalus briesei Alonso-Zarazaga and Sánchez-Ruiz (Coleoptera: Curculionidae) Ex Spain	1997 CSIRO	Widely established (Briese et al., 2002a).
	Urophora terebrans Loew (Diptera: Tephritidae) Ex France	2000 CSIRO	One release made but not established (Swirepik and Smyth, 2002).
Parthenium hysterophorus L. Parthenium(Asteraceae) Ex North America	*Carmenta ithacae* (Beutenmüller) (Lepidoptera: Sessiidae) Ex Mexico	1998 QPIF	Over 12,500 released over 30 sites.
	Puccinia melampodi Dietel and Holway(Urendales) Ex Mexico	2000 QPIF	Released at over 50 sites in central and northern Queensland. It quickly established but had little effect (Dhileepan, 2007, 2006a).
Prosopis spp. Mesquite(Mimosaceae) Ex North and South America	*Algarobius bottimeri* Kingsolver (Coleoptera: Chrysomelidae) Ex USA via South Africa	1997 QPIF	Over 99,000 released across northern Queensland (Anon, 1998). Established but significant impact unlikely (van Klinken and Campbell, 2001).
	Evippe sp. 1 (Lepidoptera: Gelechiidae) Ex Argentina	1998 CSIRO	About 62,000 released at 6 sites across northern Australia over 2 years. Establishment confirmed but abundance varied with climate. Heaviest defoliations occurred in the hottest region (van Klinken and Burwell, 2005; van Klinken et al., 2003).
	Prosopidopsylla flava Burkhardt (Hemiptera: Psyllidae) Ex Argentina	1998 CSIRO	About 183,000 released into 5 sites across northern Australia over 2 years. Tenuously established at two sites, a year after release. (van Klinken et al., 2003).
Senecio jacobaeae L. Ragwort, tansy ragwort(Asteraceae) Ex Eurasia, northern Africa	*Platyptilia isodactyla* (Zeller) (Lepidoptera: Pterophoridae) Ex Spain	1999 VicDPI	Releases made in Victoria and Tasmania. Established and having measurable impact.
Sida rhombifolia L. and *Sida acuta* Burman f.Paddy's lucerne and spinyhead sida(Malvaceae) Ex tropical America	*Eutinobothrus pilosellus* (Boheman) (Coleoptera: Curculionidae)	1997 CSIRO, NTDR	Early evidence of establishment at low densities but confirmation now needed.
Ulex europaeus L.Gorse(Fabaceae) Ex Europe	*Agonopterix ulicetella* (Stainton) (Lepidoptera: Oecophoridae) Ex Europe via Chile	2008 VicDPI, TIAR	Released in Victoria and Tasmania.

(*continued on next page*)

Table 1 (*continued*)

Weed	Agent	Date of release and research organisation	Outcome
	Cydia succedana (Denis and Schiffermüller) (Lepidoptera: Tortricidae) Ex England and Portugal	2002 TIAR, VicDPI	While release permits were issued this agent has not been released to date.
	Sericothrips staphylinus Haliday (Thysanoptera: Thripidae) Ex England, Portugal via New Zealand	2001 TIAR	Some 417 releases of 250–1000 per release in Tasmania. Establishment at most sites, albeit at low populations and little discernable damage (Ireson et al., 2008a).
	Tetranychus lintearius Dufour (Acari: Tetranychidae), Ex Europe via New Zealand	1998 TIAR, VicDPI	Releases at 116 sites in Tasmania and 90 sites in Victoria resulted in good establishment in both states (Ireson et al., 2003). By 2003 a significant reduction in dry matter production, but not flowering nor podding, indicated that it had potential as a useful agent (Davies et al., 2007).

et al., 2007) that has recently been targeted for biological control. It is also a serious weed in South Africa and the two countries are coordinating efforts. Foreign exploration in South America led by Dr. Stefan Neser has resulted in two prospective agents being brought back to South Africa and then to Australia.

The leaf beetle *Plectonycha correntina* Lacordaire was studied in Argentina (Cagnotti et al., 2007) and found to have a very narrow host range. It is presently being studied in quarantine in Australia where it looks most promising (WAP unpublished data). A second leaf beetle, *Phenrica* sp., was studied in South Africa (van der Westhuizen, 2006) and was found to have a very narrow host range. This insect is also scheduled for Australian host-testing in 2009. Further exploration will be undertaken in South America to find additional agents.

4.4. *Asparagus asparagoides* (L.) Druce

Bridal creeper, *Asparagus asparagoides*, is one of the most serious environmental weeds of southern Australia as it can change the structure, floristic composition and ecology of natural ecosystems (Morin et al., 2006b). It is a WONS.

Three agents from South Africa have been released against bridal creeper (Table 1). Two of these, the leafhopper *Zygina* sp. and the rust *Puccinia myrsiphylli*, have established widely and have already demonstrated their capacity to reduce significantly the density of bridal creeper populations. *Puccinia myrsiphylli* has had the greatest impact in suppressing the target weed in most areas released from year to year (Morin and Edwards, 2006). In contrast, *Zygina* sp. has been less reliable; its population and hence impact often fluctuating over years. Major efforts are being made to measure the impact of the rust and leafhopper using long term before-and-after monitoring at several sites across southern Australia for up to nine years and also exclusion experiments in Western Australia and New South Wales for four years.

4.5. *Baccharis halimifolia* L.

Groundsel bush, *Baccharis halimifolia*, was the target of a long-running biological control program. The weed was a serious problem in south-eastern Queensland and northern NSW particularly in dairying areas, forestry plantations and the coastal environment. Some 14 agents were released in Australia after exploration in the USA, Mexico, and Brazil (Julien and Griffiths, 1998).

After the final agent, the rust *Puccinia evadens* (Verma et al., 1996) was released and established (Table 1) the project was concluded. Three agents, the gall fly *Rhopalomyia californica* Felt, the stem borer *Hellensia balanotes* (Meyrick) and the rust, are thought to be exerting significant control. Two other agents the leaf beetle *Trirhabda bacharidis* (Weber) and the stem borer *Megacyllene mellyi* (Chevrolat) may be effective in very localised areas. The overall effectiveness of the project is presently being evaluated by Sims-Chilton et al. (2009).

4.6. *Bryophyllum* spp.

Bryophyllum delagoense (Eckl. and Zeyh.) Schinz (family Crassulaceae), known as mother-of-millions, and its hybrid *Bryophyllum* × *houghtonii* (D.B. Ward) P.I. Forst., known as hybrid mother-of-millions, have become increasingly serious weeds in Queensland and northern New South Wales over the past 50 years (Hannan-Jones and Playford, 2002). Surveys of the phytophagous fauna of Madagascar (Witt and Rajaonarison, 2004) and South Africa were undertaken from the South African Field Station from 1999 and resulted in four insects being investigated further. Host-testing of two of these, the weevils *Osphilia tenuipes* Fairmaire and *Alcidodes sedi* Marshall, commenced in South Africa (Witt, 2004; Witt et al., 2004) and was completed in Australia, but both species were able to utilise the exotic ornamental *Kalanchoe blossfeldiana* Poelln. as a host (McLaren et al., 2006). Progression of the project will depend upon approval through the *Biological Control Act* because conflicts of interest exist (McLaren et al., 2006). The thrips *Scirtothrips aurantii* Faure which was not deliberately released in Australia (Morris and Mound, 2004; Palmer, 2005) has achieved a widespread distribution and anecdotal evidence indicates that it can be severely damaging. The Australian populations of this thrips appear to have a different host range to South African populations which are pests of mangos and citrus (Manners and Dhileepan, 2005) and aspects of its taxonomy and biology are presently under investigation (Rafter et al., 2008a).

4.7. *Cabomba caroliniana* Gray

Cabomba or water fanwort, *C. caroliniana*, is a fast-growing submerged aquatic plant with the potential to infest permanent water bodies throughout the world and is a WONS. Surveys were conducted in the native range in South America including most of northern and central Argentina, southern Paraguay, southern Brazil, and Uruguay. Surveys on other *Cabomba* spp. were conducted in Venezuela, Mexico, Costa Rica and Puerto Rico. Three promising phytophagous insects have been found and studied in the native range. The aquatic weevil *Hydrotimetes natans* Kolbe (Curculionidae) is currently being tested in quarantine and appears to be host specific. Two moth species, *Paracles burmeisteri* Berg (Arctiidae) and *Paraponyx diminutalis* (Snellen), (Pyralidae), may not be adequately specific (Schooler et al., 2006, 2009). Only one species of Cabombaceae is native to Australia, aiding the probability of finding a safe biocontrol agent (Schooler et al., 2009).

4.8. *Chrysanthemoides monilifera (L.) Norlindh*

Biocontrol activity continues against both boneseed (*Chrysanthemoides monilifera* ssp. *monilifera*) and bitou bush (*Chrysanthemoides monilifera* ssp. *rotundata*) which are southern African in origin and problematic in southern Australia (Downey et al., 2007). They are collectively recognised as a WONS. Eight biocontrol agents have been released (four established) against bitou bush and seven released against boneseed (none established); the last being a leaf rolling *Tortrix* sp. and the mite *Aceria* sp. (Table 1). Research is continuing with the rust fungus *Endophyllum osteospermi* (Doidge) A.R. Wood, to gather the necessary information for an application to release (Morley and Morin, 2008). One agent, the tephritid seed fly *Mesoclanis polana* Munro, has established very well on bitou bush in northern areas where up to 99% of seed heads can be attacked (Edwards et al., 2009).

4.9. *Cryptostegia grandiflora (Roxb.) R. Br.*

Rubber vine, *Cryptostegia grandiflora*, is a major weed in northern and central Queensland and a WONS. Dense thickets hamper cattle management and pose a serious threat to native flora and fauna in riparian habitats. Following exploration in Madagascar two agents, the pyralid moth *Euclasta whalleyi* Popescu-Gorj and Constantinescu and the rust *Maravalia cryptostegiae* (Cummins) were released before 1997. While the moth has on occasion produced outbreak populations capable of defoliating large stands (Mo et al., 2000), it is the rust that has been an outstandingly successful agent. Long-term monitoring since 1997 has indicated a reduction of live plants and stems of at least 40%, a reduction of 10% of live stems per plant and a significant reduction in seedling recruitment (Vogler and Lindsay, 2002).

4.10. *Cytisus scoparius L.*

The seed beetle, *Bruchdius villosus* F. was released in Australia in 1995. In 1999 this agent was found attacking tagasaste (*Chamaecytisus proliferus* H. Christ) in New Zealand (a source of some of the Australian releases) despite having failed to oviposit on this exotic forage species during the testing for both countries. Extensive studies and further testing in the native range and in New Zealand showed that this agent had a broader host range than the early testing had suggested due to phenological separation of certain tested agent populations from the flowering cycles of potential host plants (Sheppard et al., 2006). This discovery resulted in the cancelling of the release permit for Australia and no further redistribution of this agent even though it continues to be redistributed in New Zealand. The gall mite, *Aceria genistae* (Nalepa) has finally been released (Table 1). This agent was approved for release in Australia in 2003 but then not released when the plants used for rearing in quarantine were found to be contaminated by the broom rust, *Uromyces pisi-sativi* (Pers.) Liro. Subsequent surveys revealed that the rust was widespread in Australia but the pathway of introduction is not known (Morin et al., 2006e).

4.11. *Echium plantagineum L.*

This biological control program for Paterson's curse, *E. plantagineum*, has passed into the evaluation phase (Smyth and Sheppard, 2002; Smyth et al., 2004; Swirepik and Smyth, 2002) including early economic predictions (Nordblom et al., 2002). It appears that all the six main agents have established and have spread satisfactorily. The most damaging agent in the early phase after release was the crown weevil, *Mogulones larvatus* (Schultz) (Buckley et al., 2005). However several years on and a long drought later, the flea beetle *Longitarsus echii* Koch is proving the most damaging across Australia with significant impacts (e.g. declines in herbicide costs) in most southern states (Smyth et al., 2004).

4.12. *Emex australis Steinh.*

Spiny emex, *Emex australis*, is an annual weed of cropping systems and pasture in southern Australia and particularly Western Australia. Because previous attempts at biological control were unsuccessful a further attempt was made by releasing an insect collected from a congener, *E. spinosa* (L.) Campd., in Israel which was thought to more closely match the climate of areas in Australia where spiny emex was a problem (Scott and Yeoh, 2005). Releases of *A. miniatum* did not result in establishment (Table 1).

4.13. *Fumaria spp.*

Fumaria spp. or fumitory are cropping weeds of southern Australia and most species were introduced from Europe. Consequently CSIRO has been investigating the potential for biological control. Surveys were conducted in France, 2004–2005, and three fungi and one insect, *Sirocalodes mixtus* Mulsant and Rey (Coleoptera: Curculionidae), were found and considered promising (Jourdan et al., 2008).

4.14. *Genista monspessulana (L.) L. Johnson*

A biological control program was initiated against *Genista monspessulana* (Cape, Montpellier or French broom) in 1999 using seed funding from California and the CRC for Weed Management Systems. Native range surveys were conducted and a short list of potential biological control agents developed. The first agent for which host range testing has been completed is the psyllid *Arytinnis hakani* (Loginova). As the final stages of the release application were being prepared an incursion of this species was found in the Adelaide hills in South Australia that had clearly been there for some years. The only time this agent had been deliberately imported into quarantine in Australia was in 2002. The insect is now widespread in South Australia, some impact is being observed and it is intended to have it approved as a biological control agent so that redistribution can be undertaken.

4.15. *Heliotropium amplexicaule Vahl*

Blue heliotrope, *Heliotropium amplexicaule*, is an environmental weed that has been investigated for biological control possibilities in recent years. Following survey in Argentina, one biological control agent, the leaf beetle *Deuterocampta quadrijuga* (Stål), was found to be sufficiently host-specific (Briese and Walker, 2002) and released in 2001. It has established against blue heliotrope (Table 1) and anecdotal evidence is that it is very effective in some areas. A second agent, a *Longitarsus* sp. flea beetle has undergone testing (Briese and Walker, 2008) but a release permit was not obtained.

4.16. *Jatropha gossypiifolia L.*

Jatropha gossypiifolia (bellyache bush) has been a target for biological control in Australia since 1996. Locations in nine countries (Mexico, Venezuela, Dominican Republic, Puerto Rico, Nicaragua, Netherlands Antilles, Guatemala, Trinidad and Cuba) have been investigated for potential agents. The stem-boring weevil *Cylindrocopturus imbricatus* Champion (Curculionidae) the root breeding *Colaspis* sp. (Chrysomelidae) and *Styloleptus* sp. and *Parmenonta* sp. (Cerambycidae) were imported into Australian quarantine but could not be reared. *Lagocheirus* sp. (Cerambycidae) established in quarantine, but host-testing revealed it fed on cassava and it was rejected. Preliminary studies on the rust fungus, *Phakopsora jatrophicola* Cummins ex Cummins (Uridenales) are promising and further work is ongoing. The seed feeding jewel bug, *Agonosoma trilineatum* F. (Scutelleridae) is the only agent approved for release in Australia against bellyache bush (Table 1).

4.17. *Lantana camara* L.

Lantana, a WONS, is perhaps the oldest target for biocontrol as efforts commenced with Albert Koebele's work in Mexico for Hawaii in 1902 (Perkins and Swezey, 1924). Since then several countries have sought effective agents and by 1996 some 27 agents had been introduced into Australia. The lantana story has been reviewed by Day et al. (2003b).

Two countries, South Africa and Australia, currently have active biological control programs and these countries coordinate their efforts. Three agents have been released in the last decade in Australia (Table 1).

The ornamental lantanas, from which the weed originated, have long been considered to be cultivars of hybrid origin (Sanders, 2006) but beyond that, the taxonomy has been unclear. Considerable effort is now being made to better understand the taxonomy of lantana using microsatellite markers, but variation remains very limited (R. Watts, CSIRO personal communication).

4.18. *Macfadyena unguis-cati* (L.) Gentry

Cat's claw creeper, *Macfadyena unguis-cati*, a native of South America, has become one of the more important environmental weeds of the subtropical eastern seaboard after its introduction as an ornamental plant. Its status in Australia has been reviewed by Downey and Turnbull (2007). A biological control project has been active since 2002 and two insects have now been released (Table 1). The project has been a cooperative effort between QPIF and the Agricultural Research Council-Plant Protection Research Institute (ARC-PPRI) in South Africa (Sparks, 1999), with the latter organisation undertaking the foreign exploration and agent selection component. Features of the project have been the international cooperation, investigations to determine sensitive plant functions (Raghu and Dhileepan, 2005), rigorous climate matching analyses (Rafter et al., 2008b), molecular characterisation of Australian and native genotypes to identify the native range (Sigg et al., unpublished report) and the use of stakeholder groups to mass rear and release the approved agents.

4.19. *Mimosa pigra* L.

Mimosa pigra, a WONS, has been the target of a biological control program in Australia since 1979, and shorter-term projects have been conducted in several other south-east Asian countries. Thirteen insects and two fungi have been released in Australia to control *Mimosa pigra* including five species in the last decade (Table 1). At least nine agents have established in Australia. Two agents *Carmenta mimosa* and *Neurostrota gunniella* are currently inflicting severe damage, reducing both seed production and seed banks, and defoliating plants, which favours competing vegetation and leads to lower seedling survival and increasingly senescent stands. The impact of more recently released agents, especially *Macaria pallidata* and *Malacorhinus irregularis* has not been measured, but appears to be substantial. There are abundant opportunities to release new agents in Asian and African countries where *Mimosa pigra* is a problem (Heard and Paynter, 2009).

4.20. *Nassella trichotoma* (Nees) Hack. ex Arechav. and *N. neesiana* (Trin. and Rupr.) Barkworth

The testing of three pathogens for serrated tussock and Chilean needle grass is still in progress in Argentina. These are the rusts *Puccinia nassellae* Arth. and Holw., *P. graminella* Diet. & Holw. and *Uromyces pencanus* Arth. & Holw (Anderson et al., 2006). *Uromyces pencanus* appears to be the most promising of the three because reliable methods have been developed for culturing inoculum and infecting plants (Anderson et al., 2008).

4.21. *Onopordum* spp.

Three species of *Onopordum* thistles, and their hybrids, have become serious pasture weeds in southern Australia. Biological control efforts resulted in seven insect species being released between 1992 and 2000 (Briese et al., 2002b).

Confirmed establishment of four agents has led to significant impacts by some of the biological control agents. Swirepik et al. (2008) have recorded *Lixus cardui* Olivier densities that reduced plant height by 33% and seed production by 65%. The seed weevil *Larinus latus* Herbst, also directly removed 56% of the seed produced at the sites, leading to a mean overall reduction of 84% in seed added to the soil. The significant reductions caused by these two agents augur well for the long-term success of this project.

4.22. *Parkinsonia aculeata* L.

The program against parkinsonia, a WONS, was reinvigorated in 1999 when new survey work began in tropical America. The original work done from 1983 to 1995 led to the release of three agents, none of which has contributed to control. The seed feeder, *Penthobruchus germaini* Pic, is widely established and common but seed predation rates are low (van Klinken et al., 2009). The aim of the current project is to survey in new areas in Central and South America which have not been surveyed previously (see section on biogeography). By early 2008, approximately 340 species had been recorded from a total of 190 sites in eight countries. Disappointingly, few appear to be damaging, wide ranging and common, attributes desired in biological control agents. However a list of potential agents is currently under investigation in the native range with a view to importing into Australian quarantine for further testing in 2009.

4.23. *Parthenium hysterophorus* L.

Efforts by QPIF to bring the serious pastoral and agricultural weed, and WONS, *Parthenium hysterophorus* L. under biological control have spanned some 30 years. Surveys of the native range were conducted in the United States, Mexico, Central America (McClay et al., 1995), Brazil and Argentina leading to eight insects and two plant pathogens being released. Two of these (Table 1), the moth *Carmenta ithacae* and the leaf-rust *Puccinia melampodii* were released in the last decade (Dhileepan and Strathie, 2009). It is not anticipated that there will be further efforts to look for additional agents.

Efforts have also been made to evaluate the biological control of this weed. Two agents, the leaf-feeding beetle *Zygogramma bicolorata* Pallister and the stem galling moth *Epiblema strenuana* (Walker) are considered effective (Dhileepan, 2001; Dhileepan, 2003). The various evaluation studies were used in an economic analysis which indicated substantial benefits due to biological control (Adamson and Bray, 1999; Dhileepan, 2007).

Parthenium is also a serious weed on the Indian subcontinent and an emerging serious weed in southern Africa. Cooperative arrangements have been developed between Australia and both India and South Africa so that agents released in Australia can be utilised in those areas.

4.24. Phyla canescens (Kunth) Greene

Lippia, *Phyla canescens* (Verbenaceae) is a fast-growing, mat-forming plant native to South America and invasive in Australia. Surveys for the plant and its natural enemies were initiated in Argentina in 2005 in a collaborative effort between CSIRO and USDA-ARS South American Biological Control Laboratory. At least 20 arthropods and 16 fungi were found. The most promising insects for biological control are three flea beetles (Chrysomelidae). Pathogens include the rust *Puccinia* cf. *lantanae* Farl., *Cercospora* cf. *lippiae* Ellis & Everh. and three *Colletotrichum* spp., associated with leaf spots and stem cankers. Additional information on their biology and host-specificity is required (Sosa et al., 2008).

4.25. Prosopis spp.

Three taxa of *Prosopis* spp. and their hybrids, collectively known as mesquite, are naturalised and weedy across northern Australia. Mesquite is a WONS (van Klinken and Campbell, 2001). The first efforts concentrated on two seed feeding bruchids, but they have limited impact (van Klinken and Campbell, 2009; van Klinken et al., 2009). However more recently two additional agents were released by CSIRO. One of these the leaf tier, *Evippe* sp. causes severe defoliation of mesquite in the Pilbara region of Western Australia where it is considered a successful agent.

There is presently little activity in the biological control of mesquite in Australia because existing control methods are considered adequate by the committee overseeing the national management of this weed. However, there are several species from the very large arthropod fauna (Cordo and DeLoach, 1987; Ward et al., 1977) with potential as biological control agents (van Klinken et al., 2009). Indeed several of these agents are currently being investigated by ARC-PPRI and USDA SABCL (Mc Kay and Gandolfo, 2007).

4.26. Raphanus raphanistrum L.

Wild radish is a serious cropping weed of southern Australia. The potential for its biological control was investigated by CSIRO. Surveys for potential agents were conducted from 1997 to 2001 for potential agents in the Mediterranean region. Few organisms that would be unlikely to attack canola or edible radish were found (Scott et al., 2002).

4.27. Rubus fruticosus L. aggregate

European blackberry, *Rubus fruticosus*, is a serious weed in New South Wales, Victoria and Tasmania and a WONS. The systematics of this aggregate have recently been revised (Evans et al., 2007). Eight additional strains of the leaf-rust fungus *Phragmidium violaceum* (Schultz) Winter, were tested and approved for release in 2004 to increase the genetic diversity of existing populations in Australia (Gomez et al., 2008; Morin et al., 2006a). This rust was illegally introduced in Australia in the mid 1980s (Marks et al., 1984), followed by the authorised release of a host-specificity tested strain (F15) in 1991 (Bruzzese and Hasan, 1986). The eight additional strains were sourced from a ‘trap garden’ of different Australian blackberry genotypes established at the CSIRO European Laboratory in France, and found to be genetically different from the existing rust fungus in Australia (Gomez et al., 2006; Morin et al., 2006a). A large-scale release program was established from 2006 to 2009 and molecular tools are currently being used to monitor their establishment and persistence (Morin et al., 2008). Further risk assessment activity is underway by the VicDPI on another pathogen, *Septocyta ruborum* (Lib.) Petrak in France (Baguant et al., 2008).

4.28. Rumex spp.

Many *Rumex* spp. are serious weeds in temperate high rainfall regions and irrigated pastures of southern Australia. A biological control program was initiated in 1982 against *R. conglomerates* Murray, *R. crispus* L., *R. obtusifolius* L., and *R. pulcher* L in Australia and in 1989 *Pyropteron doryliformis* (Ochsenheimer) was released. In Western Australia, *R. pulcher* populations were greatly reduced in sites where *Pyropteron doryliformis* had been released (Fogliani and Strickland, 2000). In northern Victoria *Pyropteron doryliformis* established well on *R. crispus* (Morley et al., 2004). However, this insect possibly also caused field damage to the native *R. brownii* Campd (D. Taylor, QPIF, personal communication).

4.29. Senecio jacobaea L.

Up until 1997 five biological control agents were released into Australia against ragwort (Julien and Griffiths, 1998). Since then one further biological control agent (Table 1) has been approved for release (McLaren et al., 2000). The ragwort plume moth, *Platyptilia isodactyla* (Zeller) was first released in 1999. This agent has established and evaluation is underway. Biological control of ragwort has been very successful in Tasmania due to the impacts of the flea beetle *Longitarsus flavicornis* Stephens (Ireson et al., 1991; Potter et al., 2004) though effects can be diminished where the weed grows in areas likely to have water-logged soils (Potter et al., 2007).

4.30. Senecio madagascariensis Poir.

Recent efforts for the biological control of fireweed have focussed on a rust fungus found to attack plants in the native range in KwaZulu-Natal, South Africa. DNA sequence analyses confirmed that one of the isolates collected during field surveys is *Puccinia lagenophorae* Cooke, a pathogen allegedly endemic to Australia that attacks several *Senecio* species, including fireweed. The other isolates recovered were found to be interspecific hybrids, with *Puccinia lagenophorae* as one of the parents (Morin et al., 2009). Initial pathogenicity tests showed that South African isolates produced equal or lower numbers of pustules than Australian *Puccinia lagenophorae* isolates on Australian accessions of fireweed. Further tests would be required before further consideration for introduction in Australia, but initial results are not promising. The insect fauna on *Senecio madagascariensis* in KwaZulu-Natal has not been surveyed and may be worth exploring to find possible candidate agents. However, candidate agents will be required to be highly-specific since there are several native *Senecio* spp. in Australia. Further work is likely against this target as biological control of fireweed was the only control program to be specifically earmarked for funding by the new government at the last general election in 2007.

4.31. Senna obtusifolia L.

Sicklepod, a native from the Neotropics, has become a serious weed in northern Queensland and the Northern Territory (Mackey et al., 1997). Increasing infestations of the weed, particularly in the Gulf of Carpentaria, led to efforts to find a biological control beginning in the early 1990s. Surveys within the native range through Mexico and Central America (Palmer and Pullen, 2001) and also in Brazil (Sujii et al., 1996) were undertaken. However, the results of these surveys, together with previous information (Cock and

Evans, 1984), did not reveal many prospective biological control agents suitable for Australia. The principal reason for this paucity was the fact that Australia has many native congeners to the weed such that a very high level of host-specificity would have been required.

Nevertheless, the psyllid *Mitrapsylla albalineata* Crawford was brought to Australia for host-testing but was found to have too wide a host range for release (Anon, 2002). A second insect, a gall forming weevil *Conotrachelus* sp. was also imported but attempts to rear this insect in quarantine were unsuccessful (Anon, 2002). Sicklepod remains an increasingly important weed, stakeholders are likely to request further efforts, but prospects for success seem low.

4.32. Sida acuta Burman f.

Spinyhead sida is an invasive weed in northern Australian rangelands. The biocontrol agent *Calligrapha pantherina* Stål was released in 1989 and was widely established by 1997. The beetle defoliates plants and reduces seed production. After several years of defoliation, populations of *S. acuta* were replaced by native and desirable pasture species. *Calligrapha patherina* has its greatest impact on coastal and sub-coastal areas (Flanagan et al., 2000).

4.33. Sporobolus spp.

Five grasses (*Sporobolus africanus* (Poir.) Robyns and Tournay, *S. fertilis* (Steud.) Clayton, *S. jacquemontii* Kunth, *S. natalensis* (Steud.) Dur. & Schinz, and *S. pyramidalis* P. Beauv.), collectively known as the weedy sporobolus grasses, are serious pastoral weeds in Australia, affecting productivity, property management and, ultimately, land values. Because three of the five weedy species (*S. africanus*, *S. natalensis*, and *S. pyramidalis*) originate in southern Africa, this area was a logical starting point for a biological control project. Surveys of the phytophagous fauna in southern Africa were undertaken over a two year period, 2001–2003, from the South Africa Field Station situated near Pretoria, South Africa (Witt and McConnachie, 2004). The only insect seen as a prospective biological control agent was the eurytomid wasp, *Tetramesa* sp., the larvae of which feed in the culm resulting in the malformation of the inflorescence. However all efforts to rear this species in the laboratory failed. Twenty-three pathogens, including five primary pathogens, were found on the *Sporobolus* spp. Only the leaf smut *Ustilago sporoboli-indici* L. Ling was thought promising but it was also infective on four Australian native *Sporobolus* spp. (Yobo et al., 2009) and was therefore rejected (Palmer et al., 2008). Future efforts may now concentrate on the development of a pathogen already present in Australia as a mycoherbicide.

4.34. Ulex europaeus L.

Biological control activity on gorse has had a flurry of recent activity. There has been a recent evaluation of the impacts of gorse seed weevil (Davies et al., 2008a). The gorse spider mite, *Tetranychus lintearius* Dufour, was released across affected areas after 1998 and has similar impacts to that in other countries with initial high impacts curtailed by predation of the mites (Davies et al., 2007, 2008b; Ireson et al., 2003). The gorse thrips, *Sericothrips staphylinus* Haliday, was released throughout affected areas since 2001 (Ireson et al., 2008a,b). Impact is still under evaluation, but the impacts are unlikely to suppress weedy populations. Gorse soft shoot moth, *Agonopterix umbellana* F. has been released since 2007 and mass rearing and releases continue. Finally risk assessment has been completed and a release permit obtained for the gorse pod moth *Cydia succedana* (Denis and Schiffermüller). However non-target impacts on other exotic species following release in New Zealand have so far prevented releases in Australia and additional testing of Australian natives is currently underway. Further activity has been undertaken in the native range on root feeders and plant pathogens, but no likely candidate has yet emerged.

4.35. Xanthium occidentale L.

Xanthium occidentale (Noogoora burr) is an annual from the Neotropics that is a serious weed of rangeland and agricultural regions in many parts of the world. It was one of the first weeds to be systematically targeted for biological control in Australia. Although it is now controlled by the rust, *Puccinia xanthii* Schw., in much of eastern Australia, it is still a serious invader in far northern Australia (Morin et al., 1996). CSIRO Entomology has recently collected and tested the host-specificity of strains of this rust fungus that are better adapted to the tropical climate and may control the weed in northern Australia. Exploration was undertaken in Mexico, Venezuela and the Dominican Republic in areas having similar climates to northern Australia (L. Morin, CSIRO Entomology, personal communication). The rust fungus was only found in the Dominican Republic and Mexico. Isolates imported into the CSIRO Black Mountain Containment Facility and tested for pathogenicity did not infect Australian Noogoora burr accessions. Further investigations revealed that the Noogoora burr plants from which the strains had been collected were genetically different to those present in Australia; possibly explaining why the tropical American rust strains could not infect Australian Noogoora burr. The establishment of an outdoor garden of Australian Noogoora burr accessions in tropical America may be necessary to source suitable virulent rust strains.

5. Discussion

It is evident from this discourse that Australia has been very active indeed in weed biological control in the last decade. On average at least 12 scientists and 20 technicians were working on the various projects throughout this period from several laboratories and overseas field stations. Currently we estimate Australia invests approximately AU$10–12 M per annum on weed biological control programs and about the same amount again on infrastructure support, mostly from the public purse of which half is leveraged from competitive federal or primary industry R&D funding sources.

Since 1997 Australia has had 35 active weed biological control programs against 37 weed targets. Twenty of these programs have released 43 agents (including 4 pathogens; Table 1) against 20 targets. Twenty-seven programs have undertaken host range testing of agents. Twelve of these targets are at least under partial to substantial control in some areas.

Perhaps the most strategically important document to emerge during this period was the economic analysis of Australia's weed biological control effort (Page and Lacey, 2006). The outstanding benefit/cost ratio (23:1) reported has indicated that public investment in biological control is well justified and this fact will help in attracting funds for future projects.

There has been increasing use of genetic and molecular techniques, particularly in target definition and understanding genetic bottlenecks. There have also been significant advances in agent selection, post-release evaluation approaches including non-target impacts that have international relevance. Furthermore international collaboration in weed biological control is increasing across all aspects of Australian weed biological control programs.

As in other parts of the world, policy and legislation requirements are becoming increasingly precautionary in approach and may threaten the attractiveness of biological control (Sheppard et al., 2003). For example, the recent DAFF proposal to ensure all agents proposed for release undergo a full Import Risk Assessment increases the potential processing time of applications to 2 years before a tested agent can be actually released from quarantine. Increasingly stringent standards for quarantine facilities could also have been an issue for access to such facilities, but fortunately these have coincided with the building of the new facilities to these standards.

Perhaps the outstanding successes in biological control to become evident during the period under review were those against rubber vine and bridal creeper using plant pathogens. Good levels of control were also reported for Paterson's curse, *Sida acuta*, groundsel bush, parthenium weed, docks, mesquite and mimosa while good progress was made with several others.

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